Tools and Techniques for Background Minimization in ~~Low-Background Experiments~~ LUX and LUX-ZEPLIN

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UC Grad Seminar

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Backgrounds (alternate definition)

- **My research background**
  - I got my PhD on analysis of LUX data and R&D for LZ
    - **LUX:** 350 kg target; gas/liquid xenon time-projection chamber; designed to find WIMP dark matter
    - **LUX-ZEPLIN:** ~ditto, except 350 kg -> 10 tons
  - When I started grad school, I had experience from undergraduate research in computational cosmology, focused on inflationary models
    - **Moral:** any undecided Physics grad students can switch into experimental physics, low-background physics, direct detection, etc. and I encourage you to do so!

Talk outline

- Background zoology
  - What contributes to experimental backgrounds?
    - External
    - Internal
    - Intrinsic
- Liquid xenon fundamentals
  - What do signals and backgrounds look like?
- LZ: Example background model

Stop me and ask questions at any time!

Signal and Background

WIMP Signal

- Nuclear recoil (NR)
- Single scatter
- < 25 keV_{nr}
  - Expected to follow an exponential energy distribution, but only a few events might be seen
- Flat positional distribution throughout the detection volume

Backgrounds

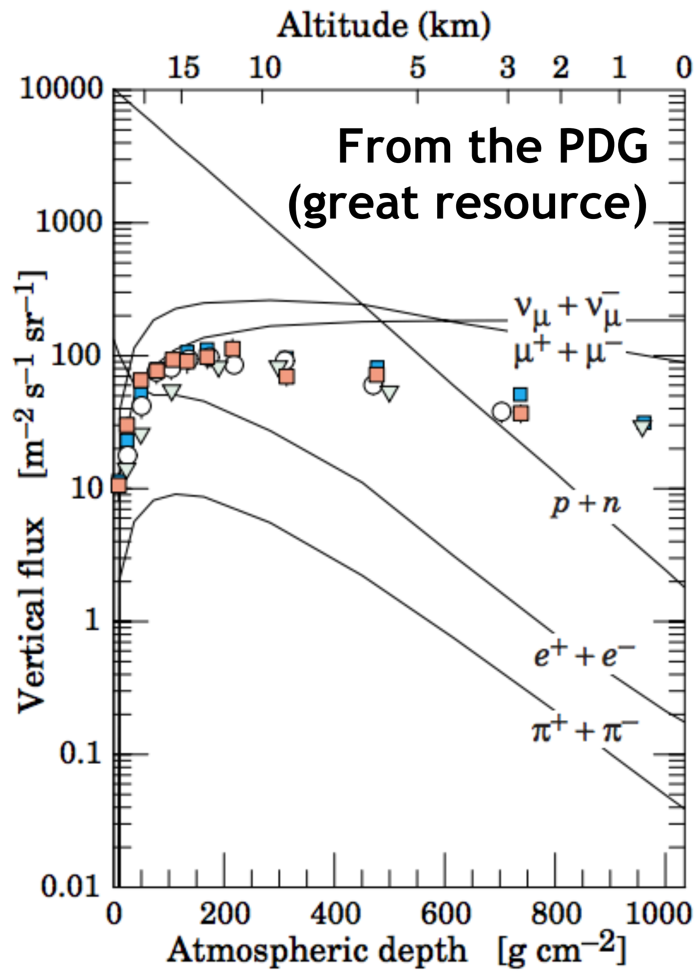
- Mostly electronic recoils (ER)
- Single and multiple scatter events
- Many energies
- ER events concentrated at the periphery of the detection volume

Backgrounds

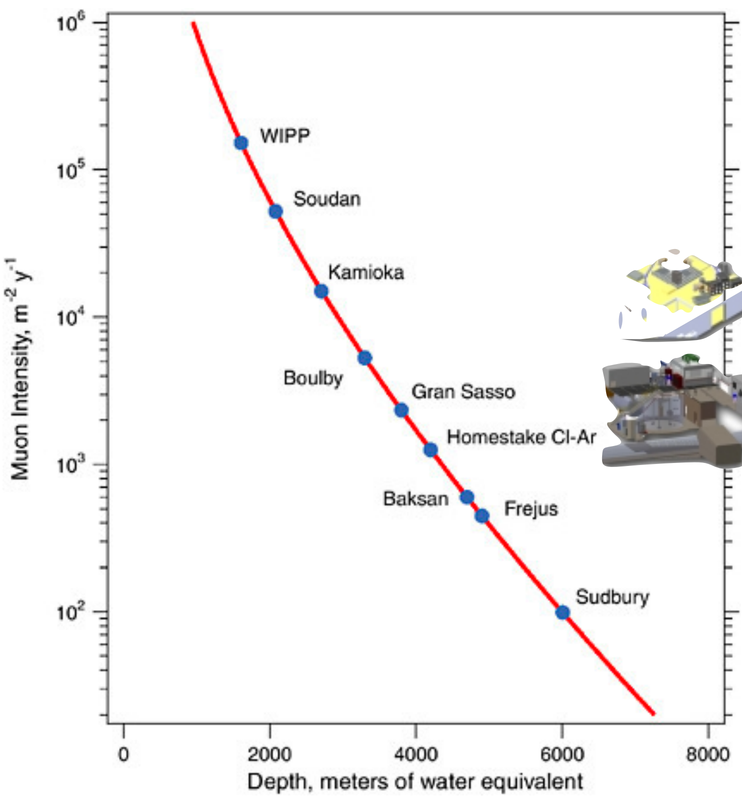
- External
  - Cosmic
  - Environmental
- Internal
  - Trace amounts of U, Th, K in materials
- Intrinsic
  - Chiefly from radioactive nobles mixed in with stable xenon
  - Also short-lived activated xenon isotopes
    - Cosmogenic
    - Neutron calibrations

External backgrounds

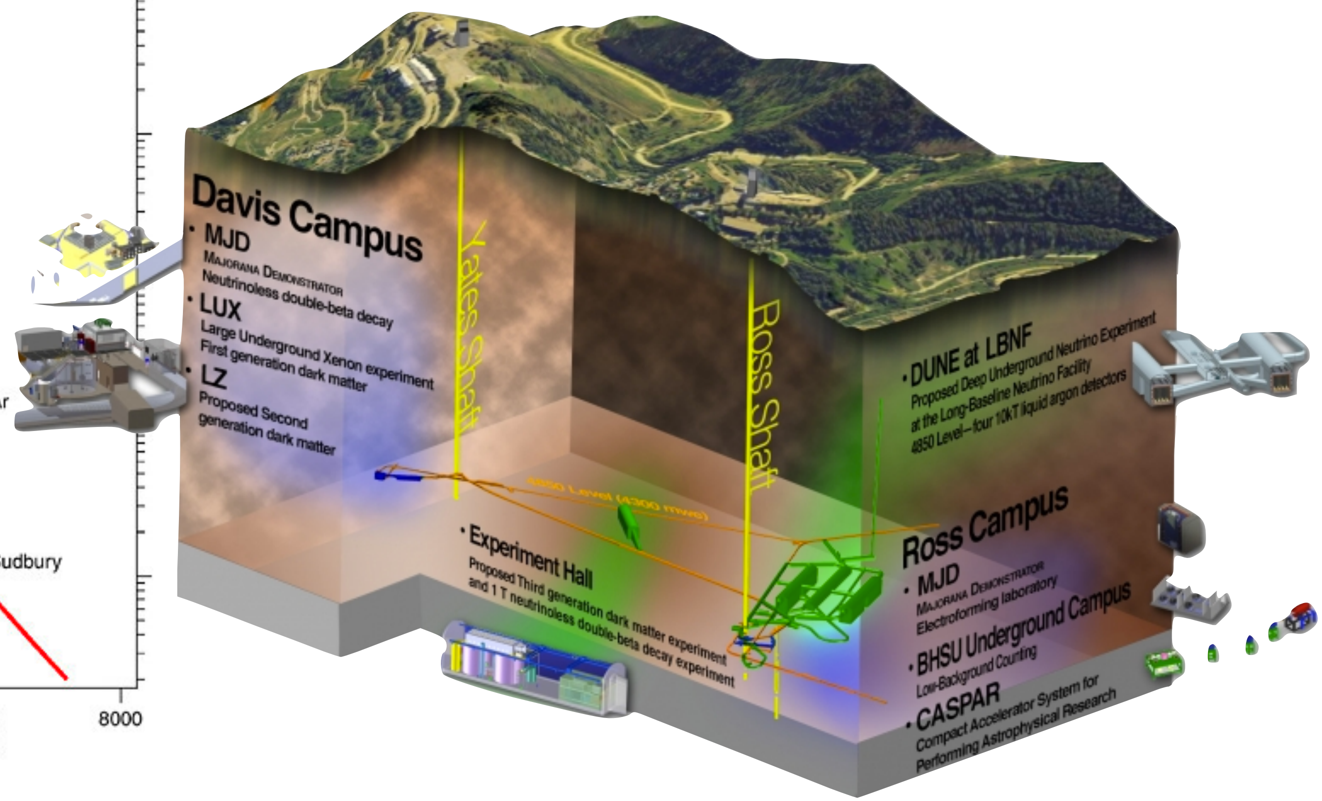
- ✦ Muons
  - Very high rate and very high energy
    - Can completely swamp a detector
    - Solution: go deep underground
  - Shielding from overburden depends on rock type
    - For comparison's sake, expressed as "meters of water equivalent" (m.w.e.)
    - Varies from mine to mine
      - SURF: 4300 m.w.e.; 3×10^6 reduction relative to surface



Underground



SURF



Muons, cont'd

- Once underground…
  - Primary concern becomes muon-induced EM and hadronic showers that create neutrons
    - Neutrons are dark-matter-like (more on this momentarily)
    - Total predicted flux at Davis Cavern of SURF: 0.5×10^{-9} *n*/ cm^2/s
    - Expected events in 1000d of LZ DM search data: <0.056 (30% systematic uncertainty)
  - Tools: muon transport code
    - MUSIC ("MUon SImulation Code") and MUSUN ("MUon Simulation UNderground") by V. Kudryatsev
      - arXiv:0810.4635; also, https://kudryavtsev.staff.shef.ac.uk/

External backgrounds

- Environmental
  - Air - must avoid leaks
    - Radon
      - More later
    - Krypton
      - ^{85}Kr: beta decay (Q = 687 keV)
    - Argon
      - ^{39}Ar: beta decay (Q = 565 keV)
      - ^{37}Ar: x-ray & auger e- (E = 2-3 keV with 90% branching)
  - Rock - choose your underground cavern wisely (and then characterize and model the one that you choose)
    - Uranium, Thorium, Potassium -> Gamma rays and neutrons
    - LUX and LZ measurements: assays of rock, gravel, and concrete; dedicated measurements with a bare HPGe
    - LUX and LZ simulations: almost completely shielded by water and vetoes

Internal backgrounds

- Every material is at least a little radioactive
  - Some materials are much better than others
  - How do you now? Assay!
    - Groups within LBNL Physics and Nuclear Divisions are leaders in this
- Rules of thumb…
  - Roughly speaking, materials closer to the target matter more
  - Ceramic materials are typically very “hot”
    - A good resistor (or capacitor) is hard to find
    - Traditional HV feedthroughs need to be strategically placed or alternative designs need to be pursued
  - Metals are a mixed bag
    - Variation: Ore to ore, supplier to supplier, batch to batch
      - If at all possible, must sample/assay from the same production batch as your detector component…
      - …or be prepared for a (possibly unpleasant) surprise!

Additional source of internal backgrounds: activation

- Example 1: Titanium
  - Muon-spallation creates fast neutrons
  - Fast neutrons in titanium -> $^{46}Ti(n,p)^{46}Sc$
    - Cross-section ~ 0.25 barns for neutrons with 5 to 20 MeV
  - ^{46}Sc
    - Beta decay followed by two gammas of ~1 MeV each
    - 84-day half-life
- Example 2: Xenon
  - Coming up…

Tools related to Internal BG

- Material screening facilities that can do…
  - Gamma spectroscopy with High-purity Germanium detectors (HPGe)
    - Better for identifying daughters of U, Th decay
    - Non-destructive; can screen actual detector components
  - Inductively-Coupled Plasma Mass Spectrometry (ICP-MS)
    - Directly measures activities of U, Th isotopes
    - Small samples; destructive
  - Neutron Activation Analysis (NAA)
  - Radon emanation measurements
    - Over-simplification: Seal, wait, flush with carrier gas into detector, count alphas or gammas
- radiopurity.org
  - Assay database of many common detector materials
  - Started at LBNL by Alan Poon

Intrinsic backgrounds

- Definition: radioactivity that permeates the target medium
- Problem manifests itself in different ways (decay type, energy, etc.) for different targets
  - Focus here is on xenon only

Intrinsic backgrounds in xenon

- Xenon is sourced from the air
  - Xe in air: 0.00004% by weight; 9×10^{-6} by volume
  - Other nobles, especially Kr, tag along
    - O(1-100 ppb) Kr/Xe in research-grade xenon
    - LZ requirement: <0.015 ppt
- Chief concern among contaminants: ^{85}Kr
  - Anthropogenic
    - Produced in nuclear fuel reprocessing and weapons testing
  - Beta decay (Q=687 keV) with >99% branching and 10.8-yr half-life
- Lighter nobles (e.g. ^{39}Ar) are subdominant

Intrinsic backgrounds in xenon

- The xenon itself!
- Activated xenon
  - Isotopes ($t_{1/2}$): ^{127}Xe (36d), ^{129m}Xe (9d), ^{131m}Xe (12d), ^{133}Xe (5d)
  - Produced by cosmogenic or neutron activation
    - Want to know more? Talk to Kelsey Oliver-Mallory
- Most concerning: ^{127}Xe
  - Undergoes electron capture
    - 85% K-shell at 33 keV
    - 15% of decays are L-shell or higher
      - 5.2 keV or less deposited via X-ray or Auger e- cascade
  - Most decays vetoed due to subsequent ^{127}I de-excitation with energy of either 203, 375, or 619 keV

Others

- Radon plate-out
  - "Phenomenon in which charged radon progeny are deposited onto the surface of materials exposed to air"
    - Air: O(10-100 Bq/m^3) of ^{222}Rn
  - Largest background component in LZ
  - Radon itself is short-lived (<4d half-life)
  - Progeny
    - ^{210}Pb: 22.3y; alphas that can create (alpha, n) reactions
    - ^{206}Pb: end-of-chain (stable), but its recoiling nucleus is of concern; high rate near walls and often looks NR-like
- Solutions
  - Reduce dust and radon in spaces where parts are made and assembled
  - Package things well and keep things as clean as possible

LZ Background Table

	Mass (kg)	$^{238}U_e$	$^{238}U_l$	$^{232}Th_e$	$^{232}Th_l$	^{60}Co	^{40}K	n/yr	ER (cts)	NR (cts)
		mBq/kg								
Upper PMT Structure	40.5	3.90	0.23	0.49	0.38	0.00	1.46	2.53	0.05	0.000
Lower PMT Structure	69.9	2.40	0.13	0.30	0.24	0.00	0.91	6.06	0.05	0.001
R11410 3" PMTs	91.9	71.6	3.20	3.12	2.99	2.82	15.4	81.8	1.46	0.013
R11410 PMT Bases	2.8	288	75.8	28.4	27.9	1.43	69.4	34.7	0.36	0.004
R8778 2" Skin PMTs	6.1	138	59.4	16.9	16.9	16.3	413	52.8	0.13	0.008
R8520 Skin 1" PMTs	2.2	60.5	5.19	4.75	4.75	24.2	333	4.60	0.02	0.001
R8520 PMT Bases	0.2	213	108	42.2	37.6	2.23	124	3.62	0.00	0.000
PMT Cabling	104	29.8	1.47	3.31	3.15	0.65	33.1	2.65	1.43	0.000
TPC PTFE	184	0.02	0.02	0.03	0.03	0.00	0.12	22.5	0.06	0.008
Grid Wires	0.8	1.20	0.27	0.33	0.49	1.60	0.40	0.02	0.00	0.000
Grid Holders	62.2	1.20	0.27	0.33	0.49	1.60	0.40	6.33	0.27	0.002
Field Shaping Rings	91.6	5.41	0.09	0.28	0.23	0.00	0.54	10.8	0.23	0.004
TPC Sensors	0.90	21.1	13.5	22.9	14.2	0.50	26.3	24.8	0.01	0.002
TPC Thermometers	0.06	336	90.5	38.5	25.0	7.26	3360	1.49	0.05	0.000
Xe Tubing	15.1	0.79	0.18	0.23	0.33	1.05	0.30	0.64	0.00	0.000
HV Components	138	1.90	2.00	0.50	0.60	1.40	1.20	4.90	0.04	0.001
Conduits	200	1.25	0.40	2.59	0.66	1.24	1.47	5.33	0.06	0.001
Cryostat Vessel	2410	1.59	0.11	0.29	0.25	0.07	0.56	124	0.63	0.013
Cryostat Seals	33.7	73.9	26.2	3.22	4.24	10.0	69.1	38.8	0.45	0.002
Cryostat Insulation	23.8	18.9	18.9	3.45	3.45	1.97	51.7	69.8	0.43	0.007
Cryostat Teflon Liner	26	0.02	0.02	0.03	0.03	0.00	0.12	3.18	0.00	0.000
Outer Detector Tanks	3200	0.16	0.39	0.02	0.06	0.04	5.36	78.0	0.45	0.001
Liquid Scintillator	17600	0.01	0.01	0.01	0.01	0.00	0.00	14.3	0.03	0.000
Outer Detector PMTs	205	570	470	395	388	0.00	534	7590	0.01	0.000
OD PMT Supports	770	1.20	0.27	0.33	0.49	1.60	0.40	14.3	0.00	0.000
Subtotal (Detector Components)									6.20	0.070
^{222}Rn (2.0 μBq/kg)									722	-
^{220}Rn (0.1 μBq/kg)									122	-
^{nat}Kr (0.015 ppt (g/g))									24.5	-
^{nat}Ar (0.45 ppt (g/g))									2.47	-
^{210}Bi (0.1 μBq/kg)									40	-
Laboratory and Cosmogenics									4.3	0.06
Fixed Surface Contamination									0.19	0.37
Subtotal (Non-ν counts)									922	0.50
^{136}Xe $2\nu\beta\beta$									67	0.00
Astrophysical ν counts (pp + ^{7}Be + ^{13}N)									255	0.00
Astrophysical ν counts (^{8}B)									0.00	0.00
Astrophysical ν counts (hep)									0.00	0.21
Astrophysical ν counts (diffuse supernova)									0.00	0.05
Astrophysical ν counts (atmospheric)									0.00	0.46
Subtotal (Physics backgrounds)									322	0.72
Total									1,244	1.22

- Extensive assay
- Careful accounting
- Once the activities are known…
  - Simulate the detector geometry
  - Turn the assay data into background event predictions

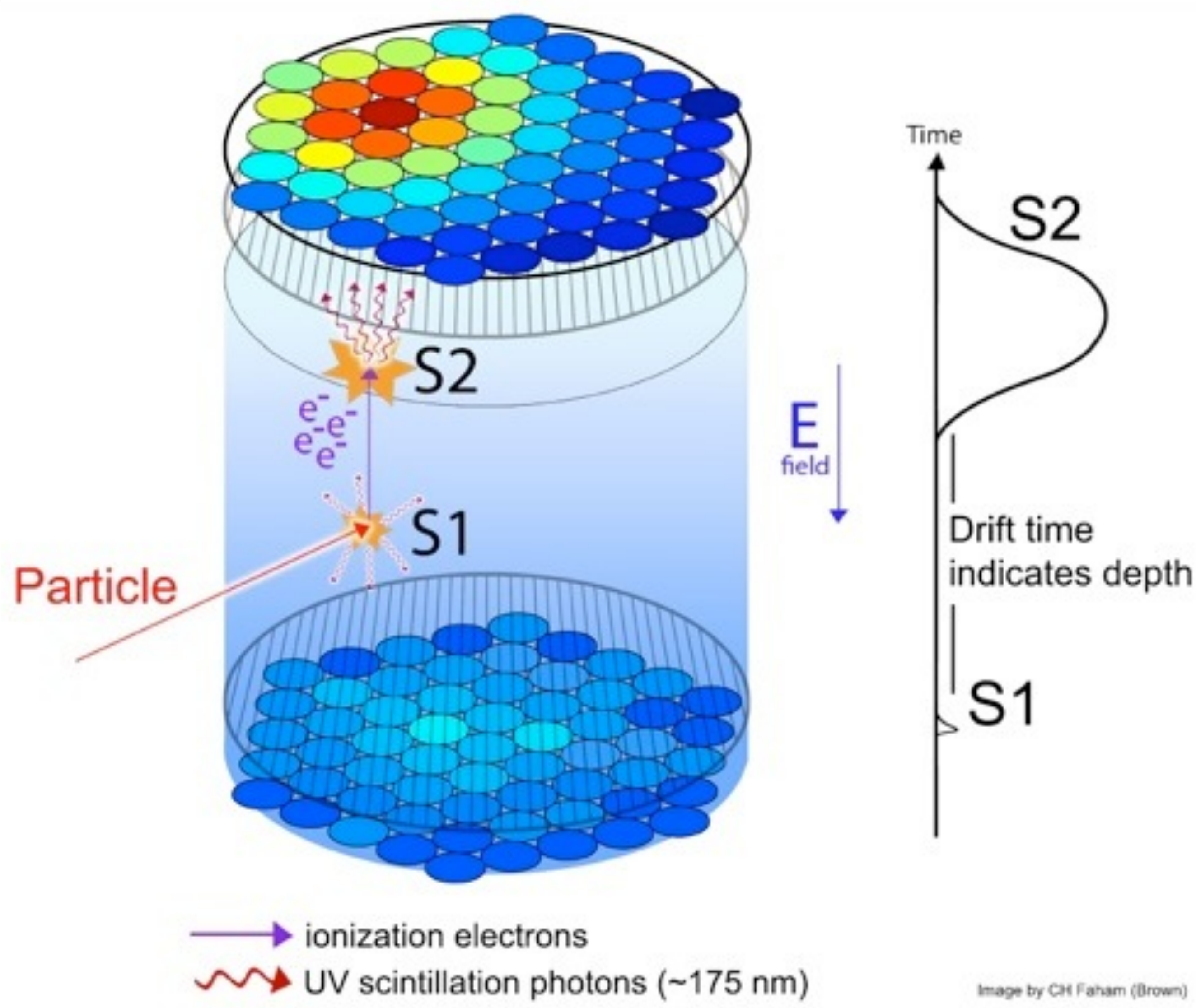
Tools of the Trade

- LUXSim and LZSim
  - GEANT-based
  - High-fidelity model based on CAD drawings
  - Inputs: materials for the drawings; libraries with activities for the materials
  - Outputs: deposited energy and location
- Noble Element Simulation Techniques (NEST)
  - Turns deposited energies into numbers of photons and electrons, or even into detector quantities
  - Works for a variety of different incident particles
- ACTIVIA
  - Predicts activation isotopes based on exposure and input neutron energy spectrum

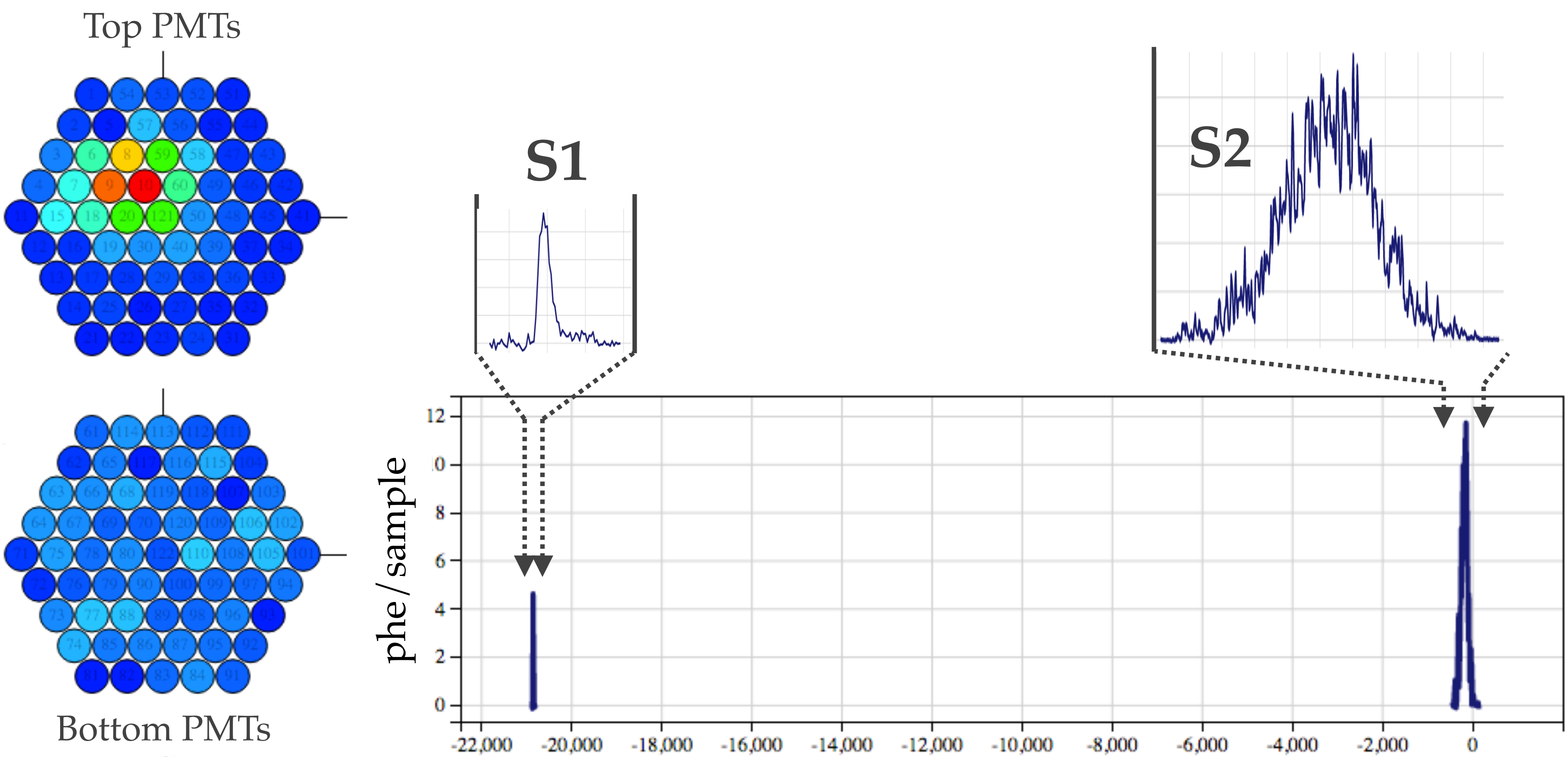
Methods for observing a xenon target

- Light and charge are the most broadly used channels for low background experiments
  - XMASS, Kamland-Zen: light only
  - EXO, LUX, XENON-100, XENON-1T, LZ: light and charge
- Time-projection chamber (TPC) design is used broadly
  - 3D reconstruction
  - Scalable

Time-Projection Chamber



Time-Projection Chamber

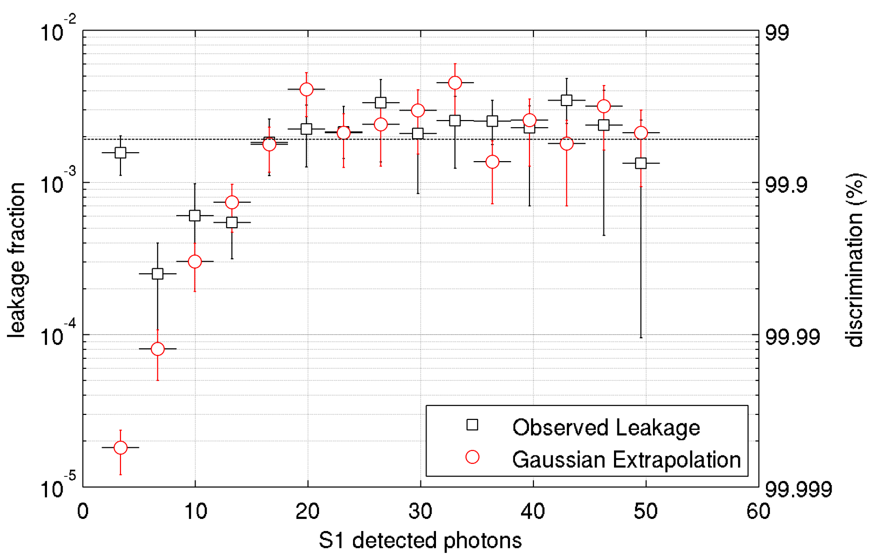


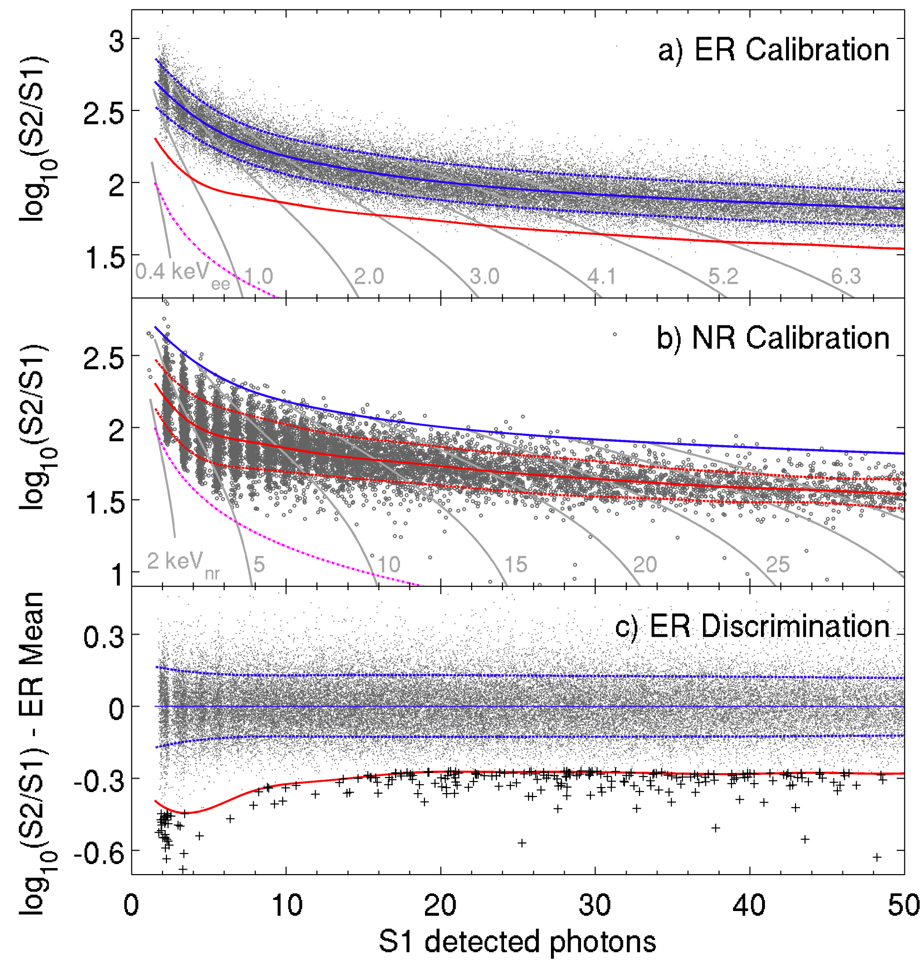
ER/NR Discrimination

- The most valuable tool in LXe detectors: ratio of charge to light
  - “Charge to light” == S2/S1 in detected quantities
  - Electronic recoils (ER): larger S2/S1
  - Nuclear recoils (NR): smaller S2/S1
- WIMPs will not interact with xenon’s electrons -> NR
- Photons, betas -> ER

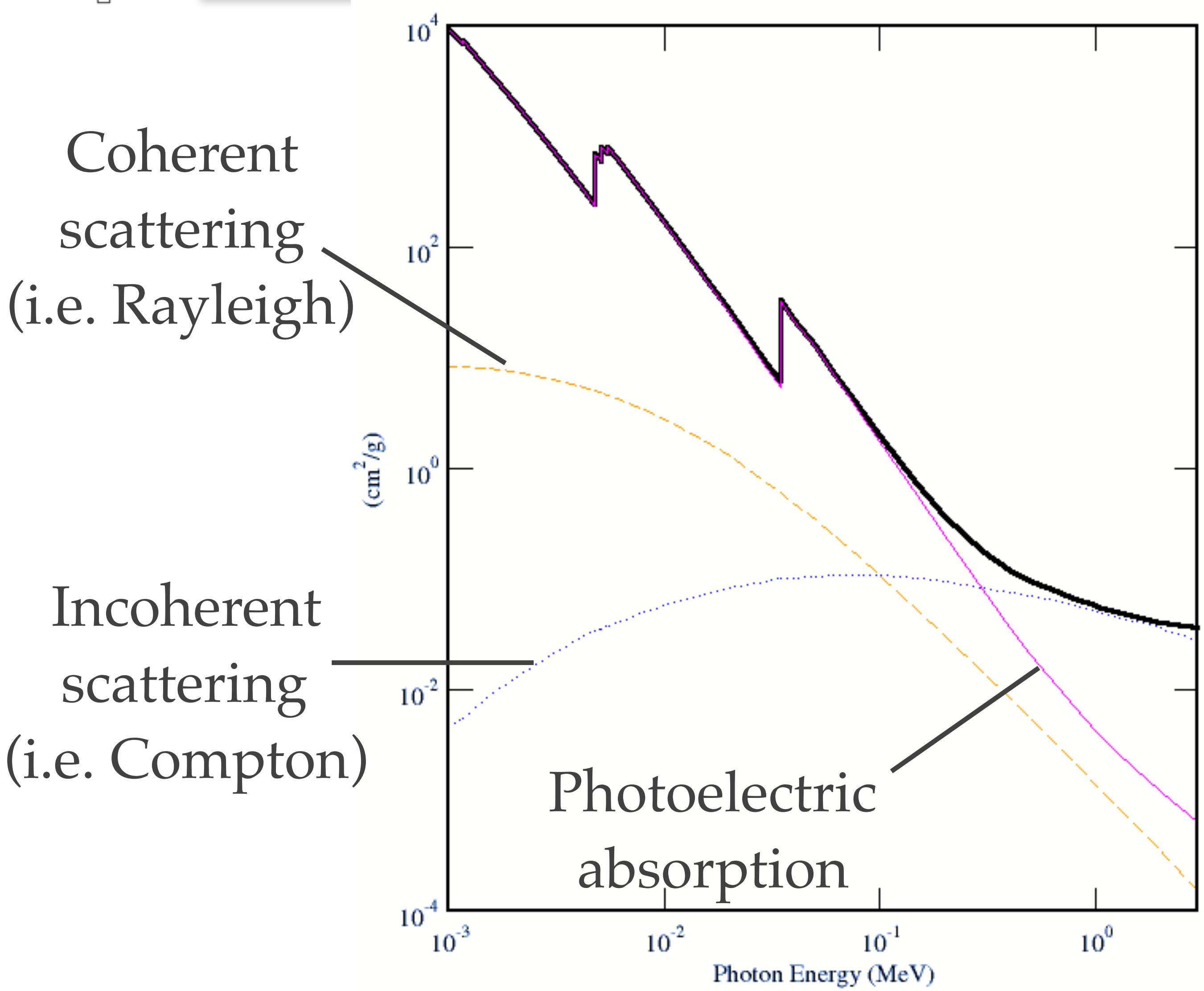
ER/NR Discrimination in practice

- ✦ LUX: 99.8% avg. ER discrimination





Photon interactions in xenon



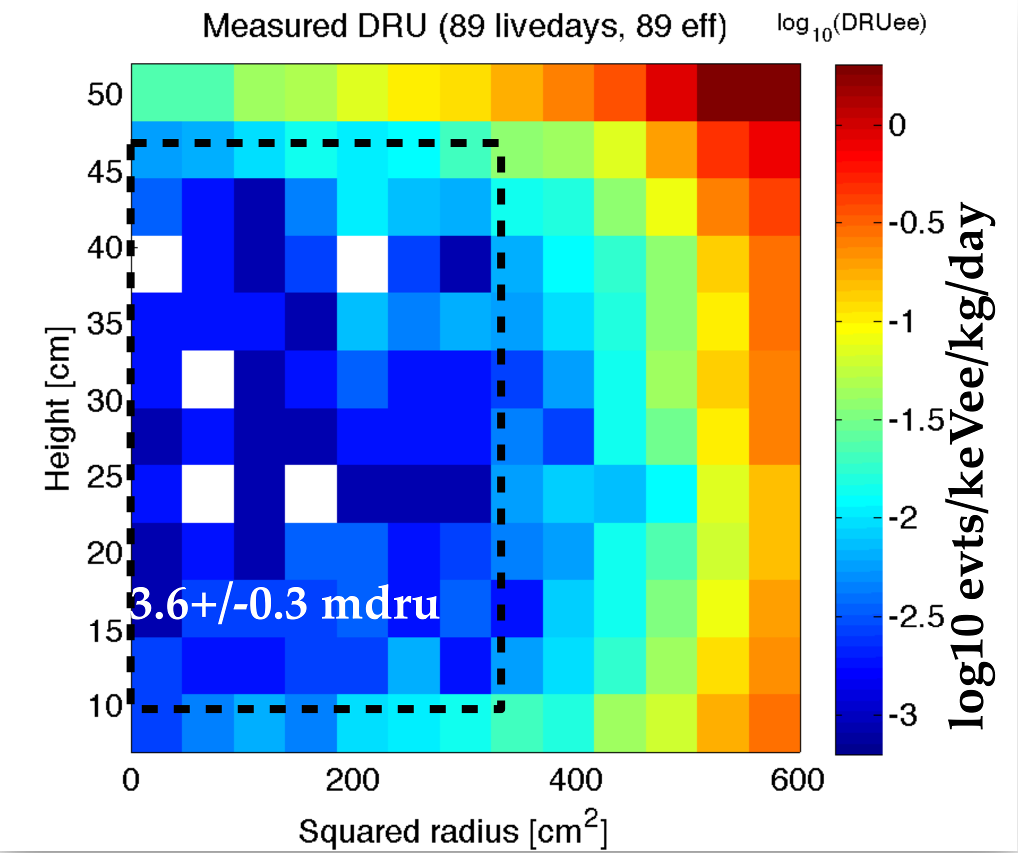
Multiple scatter rejection is an extremely powerful tool to reduce background backgrounds at high energy.

High energy gammas are likely to Compton scatter and deposit energy in more than one location within a detector.

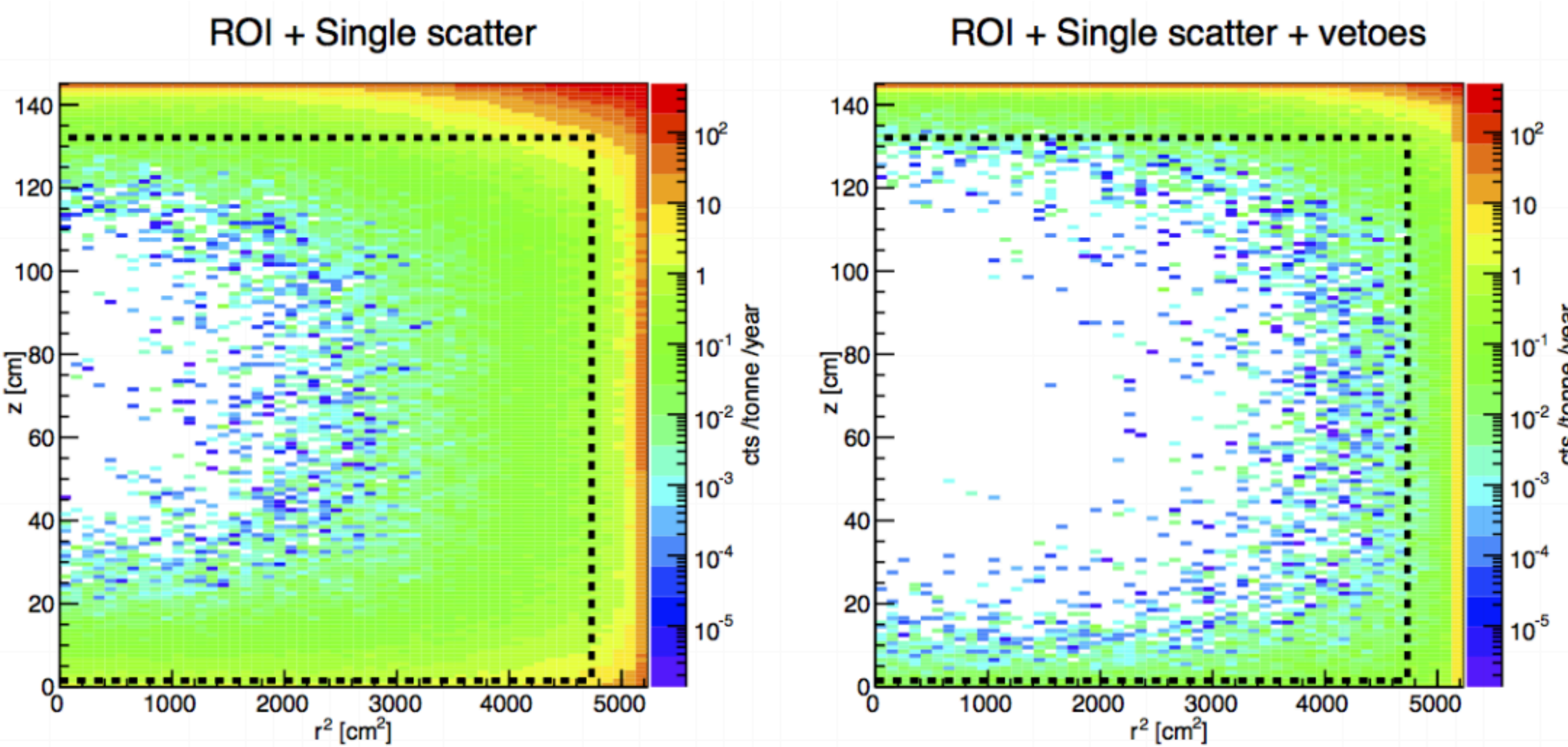
TOOL: Multiple scatter identification and rejection!

Related: fiducialization

- Xenon is dense and it has lots of electrons
  - Extremely short attenuation lengths for low energy photons and betas in liquid xenon
  - ~few cm of xenon serves to “self-shield” an inner volume
    - That inner volume is called the fiducial volume
- Powerful since the high activity components are near the periphery
  - PMTs, titanium
- External vetoes allow the volume to extend further towards the edges



Related: fiducialization



Recall: Background Zoo

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Subtotal (Physics backgrounds)									322	0.72
Total									1,244	1.22
Total (with 99.5 % ER discrimination, 50 % NR efficiency)									6.22	0.61
Sum of ER and NR in LZ for 1,000 d, 5.6 tonne FV, with all analysis cuts									**6.83**	

- The LZ background modeling show an expected >1200 ER events and ~1.2 NR events after the incorporation of all vetoes and fiducialization.
- Assuming 99.5% discrimination, 6.83 DM-like events from backgrounds in 1000 days
  - Note that even with exhaustive effort to select clean materials and design for low backgrounds, ER discrimination is a vital "tool."

More info

- LZ Technical Design Report
  - Dense and exhaustive but lots of goodies about how LZ will minimize backgrounds

Thank you

- Feel free to reach out with questions/ comments
  - Email: ekpease@lbl.gov